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Bed Erodibility at Indian River Inlet

by Trimbak M. Parchure

Prepared for U.S. Army Engineer District, Philadelphia

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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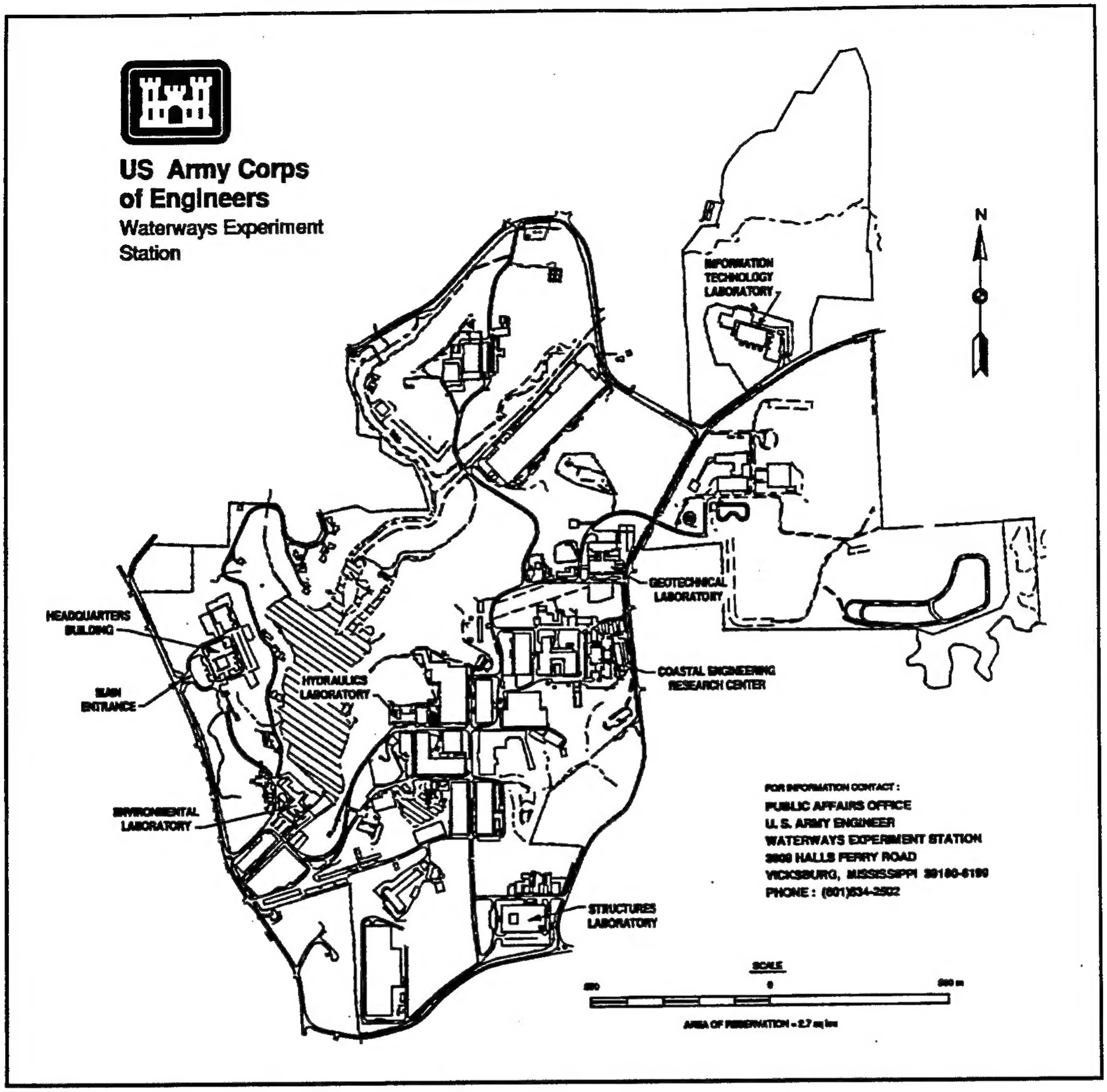

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Contents

Preface

The study described herein was performed by personnel of the Hydraulics Laboratory of the U.S. Army Engineer Waterways Experiment Station (WES) in support of the continuing evaluation of the stability of Indian River Inlet, Delaware, by the U.S. Army Engineer District, Philadelphia (NAP). NAP liaison was Mr. Gordon T. Stevens.

The study was conducted under the general supervision of Messrs. Richard A. Sager, Acting Director of the Hydraulics Laboratory; Robert F. Athow, Acting Assistant Director of the Hydraulics Laboratory; William H. McAnally, Jr., Chief of the Waterways and Estuaries Division, Hydraulics Laboratory; and Allen M. Teeter, Leader of the Sedimentation Engineering and Dredging Group, Waterways and Estuaries Division. Dr. Trimbak M. Parchure and Messrs. Teeter and Douglas B. Brister, all of the Sedimentation Engineering and Dredging Group, and Joseph M. Parman, Prototype and Field Studies Group, Hydraulics Laboratory, conducted the analyses described herein. Dr. K. Arulandan of Geoelectronics, Inc., Davis, CA, performed rotating annulus erosion tests using facilities at the University of California at Davis. Dr. Parchure prepared this report.

During the preparation and publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
pounds (force) per square foot	47.88026	pascals

1 Introduction

Background

Indian River Inlet in the State of Delaware connects the estuarine system of Indian River Bay and Rehoboth Bay to the Atlantic Ocean (Figure 1). Prior to 1938 the inlet migrated along the shoreline. In order to stabilize its location, the Corps of Engineers constructed two parallel jetties at the mouth leaving a 500-foot-wide opening for recreational navigation. Severe erosion has occurred within Indian River Inlet over the subsequent years. By the year 1995, the maximum depth of local erosion has reached about 110 feet in an area west of the existing bridge near the mouth of the inlet. It is feared that the erosion may extend spatially and endanger the riprap stability. The U.S. Army Engineer District, Philadelphia, requested the Waterways Experiment Station to collect field data and to investigate the reasons for such severe erosion. The aspects of bed erodibility based on properties of bed material are briefly described in this note.

Purpose

The purpose of the work described here was to characterize bottom sediments in Indian River Inlet in terms of their erodibility. These results can be used in analytical and numerical computations to assess the probability of future erosion in the inlet.

Consideration of the hydrodynamic aspects is beyond the scope of this report. These have been discussed in detail in the report prepared by the Committee on Tidal Hydraulics (1994). ADCP field data on current measurement at site have been reported by the WES team.[1] Strong currents with maximum velocity on the order of 7 to 8 feet per second and a complex flow pattern over water depth in the inlet region were revealed in these observations.

[1] T. C. Pratt, C. Callegan, and J. Parman, June 20-24, 1994, Indian River Trip Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

2 Surface Bed Samples

The Waterways Experiment Station conducted a field study at the site in June 1994, during which two tide gages were installed at the site, current observations were taken using an Acoustic Doppler Current Profiler, and surface bed samples were collected at ten locations. The bed samples at nine locations were obtained with a clam shell sampler and one bed sample was obtained with a drag bucket sampler. Because of the high velocity of flow within the inlet area, sampling could be done only at the slack periods of low flow velocity, which lasted only for about 30 minutes at high water and low water stage of each tide. The locations of bed samples are shown in Figure 2.

Characterization of Surface Bed Samples

Sediments are classified into two main categories for their characterization. Those which are the size of clay particles (smaller than 0.002 mm), are called cohesive sediments. All other sediments larger than the clay particles are called non-cohesive sediments. This distinction is based primarily on the fundamental property of bonding together of primary particles, called "flocculation", which is exhibited only by clay particles. Individual grains of coarse sediments do not ordinarily attach to each other and are therefore termed as non-cohesive sediments.

The clay minerals which form cohesive sediments have several properties significantly different from the properties of coarse sediments. They differ not only in terms of particle size, but also in terms of chemical composition, shape of primary particles, specific surface area, electrical charge and so on. Unlike sand, the properties of fine sediments are also affected by parameters such as temperature, chemical composition and pH of eroding fluid, organic contents, presence of non-clay minerals and coarse sediments and so on. Due to these differences, the erosional, depositional and transportation properties of cohesive and non-cohesive sediments are significantly different from each other. Out of ten samples collected at the site, six were identified as coarse sediment. Table 1 gives the visual description of the samples along with the measured median size of six samples which contained predominantly sand.

Table 1
Particle Size of Surface Bed Samples

Sample	Description	d_{50} (mm)
1	Sand	2.1
2	Sand + Shell	1.4
3	Silt + clay	* 1
4	Sand	1.7
5	Gravel + Shell	* 2
6	Sand	1.5
7	Silt + Clay	* 3
8	Silt + Clay	* 4
9	Sand	0.68
10	Sand + Clay	0.38

Legend:
* 1 : 82.75% of sediment is finer than silt (0.064 mm)
* 2 : 76.95% of sediment is finer than silt (0.064 mm)
* 3 : Size distribution not done, sample very dissimilar, containing gravel and shell
* 4 : 84.68% of sediment is finer than silt (0.064 mm)

A wide diversity of sediment from stiff clay to large gravel exists in the area. A general description of the type of sediment found at each location along with he median size data are shown on Figure 3. It is noted from the limited data that there is no specific pattern in the variation of bed material in this area. Size distribution curves for samples collected at locations 1, 2, 4, 6, 9, and 10 are given in Figures 4 to 9.

The erosional properties of cohesive sediments depend on a large number of parameters. While it is neither practical nor essential to determine the magnitude of each parameter for each sample, it is often necessary to determine some of the fundamental parameters so that the results of erosion tests could be related to these properties.

Samples collected at locations 3, 7, and 8 contained a substantial amount of silt and clay. Hence these were first analyzed to determine the relative quantities of silt and clay. The same samples were also analyzed to determine organic matter, bulk density, and moisture content. The results are shown in Table 2.

Table 2 Analysis of Sediments with Predominant Mixtures of Silt and Clay			
Parameter	Sample Number		
	3	7	8
Fraction of Total Sample in terms of clay, silt and sand			
% Clay	23.44	27.39	19.50
% Silt	59.31	49.56	65.18
% Sand	17.25	23.06	15.32
Sediment finer than Silt	82.75	76.95	84.68
Split of Silt and Clay from the mixture finer than silt (0.064 mm)			
% Silt	71.67	64.41	76.97
% Clay	28.33	35.59	23.03
Other Properties			
% Organic matter	3.46	5.41	3.39
Bulk Density	1.24	1.14	1.12
% Moisture	60.19	72.58	52.61

Sediment Core Samples

The Philadelphia District took core samples from three bore holes on both sides of the bridge in order to ascertain the depth variation of sediment. Locations of bore holes are shown in Figure 10. Out of these, two segments of sediment core taken at location marked as KFB-31 were sent to WES for analysis. The cores were mailed in 3-inch-diameter brass tubes, each about 30-inches long with a two-foot long sediment core obtained from the depths of 44-46 feet (KFB-31 U-1) and 74-76 feet (KFB-31 U-3). The cores were cut at WES into three equal segments and a 1-inch thick slice on each side of the mid-section was used for sediment characterization. It was seen that the sample contained very little sand. Hence the relative split of sand and silt plus clay was determined. The results are given below.

Sediment from KFB-31 U1 (44 - 46 feet)

Slice 1

Sand	0.62 %
Silt + Clay	99.38 %
Bulk Density	1.75 g/cm^3

Slice 2

Sand	2.45 %
Silt + Clay	97.55 %
Bulk Density	1.85 g/cm^3

Sediment from KFB-31 U3 (74 - 76 feet)

Slice 1

Sand	1.97 %
Silt + Clay	98.03 %
Bulk Density	1.55 g/cm^3

Slice 2

Sand	1.07 %
Silt + Clay	98.93 %
Bulk Density	1.35 g/cm^3

The amount of silt plus clay in sediment located at 44-46 feet depth and at 74-76 feet depth is considerably greater than that at the bed surface. The bulk density of sediment is generally expected to increase with depth below surface due to increased compaction. It is, however, noticed that the bulk density of samples at 74-76 feet depth is lower than that at higher elevations. The reason for the lower values is the presence of charred wood fragments, which have a density considerably lower than sand, found in sediment samples from lower depth.

General Comments on Erodibility of Sediment

The shear stress a on sediment bed is generated by waves and/or by flow of water and is denoted by (T_b). The bed shear strength of soil is denoted by T_s. For cohesive sediment beds, the shear strength (T_s) generally increases with depth in the sediment bed. The minimum value of T_b at which erosion of bed surface commences is termed as the Critical Shear Stress for Erosion (T_c). Under typical tidal flows the velocity and hence the flow-induced bed shear stress varies with time. When T_b becomes slightly greater than T_c , surface erosion commences and it continues over depth as long as T_b is greater than T_s. The rate of erosion varies with the soil characteristics as well as with the magnitude of excess shear stress (T_b - T_c).

Erodibility of sand and coarser sediment can be estimated analytically from published literature. Different size classes of sediment will move whenever their respective values of critical shears stress for erosion are exceeded by the flow-induced bed shear stress in the field. If it is necessary to represent the entire sample by a single value, the median size d_{50} is often used. It is seen from Table 1 that d_{50} for sand at the site varied from 0.68 to 2.1 mm. Estimated values of T_c for the range of sediment found at Indian River Inlet are given in Table 3. These are based on procedures reported in literature.

Table 3
Estimated Values of Critical Shear Stress

Type of Sediment	Critical Shear Stress for Erosion	
	Pascal (P_a)	lb/ft^2
Sand, diameter = 0.5 mm	0.29	0.006
Sand, diameter = 2.0 mm	1.44	0.03
Sand, diameter = 5.0 mm	5.75	0.10
Gravel, diameter = 10 mm	9.58	0.20

It is not necessary to conduct erosion experiments on non-cohesive sediments because research results of such experiments have been abundantly reported in the literature and several erosion rate formulae are available which use the sediment characterization results and flow parameters as input for computations. Reference may be made to Simmons and Senturk (1977) and to Graf (1979). Bed load and suspended load are estimated separately for the non-cohesive sediments. Also, the sediment carrying concept applies to non-cohesive sediments, according to which net erosion occurs if the supply of sediment to the area under consideration is less than the transporting capacity of flow.

Sediment transport rates are calculated by using different transport functions. A total of 13 selected functions for estimating bed material load are listed in the user's manual for HEC-6 (U.S. Army Engineer Hydrologic Engineering Center 1993). These transport functions have been developed over the years from 1930 to 1990. There is no single function which is universally applicable. The selection needs to be made by the user, sometimes by trial and error method, to determine which function is best suited for a given site and for the available field data used for verification. The Committee on Tidal Hydraulics (1994) selected the Ackers-White transport function. The difference between estimated sediment carrying capacity and the actual sediment transport determines whether to expect scour or deposition at the site under consideration.

Erosional and depositional processes of fine sediments are much more complex since they depend upon as many as 32 different parameters. It is not possible to provide a simple relationship between particle size and erodibility under given flow conditions. It is therefore essential to conduct laboratory experiments to determine their erodibility. The laboratory experiment results have certain limitations. For instance, the maximum size of an eddy in a laboratory device is restricted by the size of the apparatus used. Also, the turbulence structure in a vertical cylindrical device as well as in a rectangular closed-loop sediment tunnel is different from that in a deep, natural tidal channel with unsteady flows. However, in spite of the limitations of devices,

conducting laboratory experiments is still the only reliable method available for estimating erodibility of fine sediments.

3 Erosion Experiments

Erosion Equipment and Experimental Procedure

Laboratory erosion experiments were conducted at WES by using two devices:

a. Particle Entrainment Simulator (PES), shown in Figure 11, and

b. Vertical Loop Sediment Tunnel, shown in Figure 12.

Bed shear stress is induced in the PES by means of a vertically oscillating perforated disc, whereas propeller-generated horizontal flow is used for this purpose in the sediment tunnel. Both the devices were calibrated for controlling bed shear stress. The maximum bed shear stress generated in PES is 0.7 Pa, while in the sediment tunnel it is 3.0 Pa. Sediment collected in the field was used for forming a bed in the laboratory devices. Salt water of 35 ppt concentration constituted in the laboratory was used as the eroding fluid in both the devices. The usual practice is to start each experiment with no flow condition and then to increase the bed shear slowly until erosion commencement is seen visually. This provides the value of critical shear stress for commencement of surface erosion (T_c). The bed shear stress is then increased in steps and each step is maintained over a fixed duration. Samples of suspended sediment are withdrawn from the erosion device from time to time and the suspension concentration is determined. These data are used to determine the erosion rate as a function of time and bed shear stress.

Erosion Experiments on Surface Samples

Two of the four samples containing a large percentage of silt and clay, namely # 7 and # 8, were selected for conducting erosion tests. It was determined that neither of these samples eroded at bed shear stresses generated by the WES apparatus. Hence these two samples were sent to the University of California, Davis, for conducting erosion experiments in a rotating cylinder erosion apparatus (Figure 13). The erosion apparatus has been described by Lee and Mehta (1994).

Two experiments were conducted on sample # 7 in the rotating cylinder. In the first experiment, an intact sample as collected in the field was used, whereas, in the second experiment the sample was molded during its placement in the erosion device. The critical shear stress for erosion in the first case was 5.8 Pa whereas in the second case it was 4.0 Pa. The results are consistent with expectations that molding results in breaking inter-particle bonds and thus reduces shear strength. For the same reason, the samples obtained from the field are already disturbed to some extent during collection, packing and transport and hence are expected to have lost some of their strength. Erosion experiments were conducted on this sample for a range of bed shear stresses varying from zero to 16 Pa. The rates of erosion for the two conditions described above are shown in Figure 14.

It has been reported in the literature that the properties of eroding fluid can have a major effect on sediment erodibility. Hence the effect of eroding fluid composition was determined in the rotating cylinder apparatus for sample # 8. Again two experiments were conducted. In the first experiment the eroding fluid was sea water with 35 ppt salt concentration and in the second experiment distilled water was used as eroding fluid. The results are given in Figure 15. While the critical shear stress for erosion in the first case was 4.2 Pa, it was only 1.8 Pa in the second case.

In estuaries, salinity decreases in upstream reaches due to heavy rainfall or runoff. Water with lower salinity may be responsible for excess erosion due to weakening of surface layer by the concentration gradients in salinity. Presence of higher bed shear stresses resulting from higher flow rates caused by rainfall is an additional factor for increased erosion. However, at Indian River Inlet the fresh water inflow is usually insignificant compared to the tidal exchange. Hence the erosion tests reported with distilled water are of limited interest in the context of the present report. If salinities in Indian River Bay were reduced by rare heavy rainfall, erosion rates would be affected.

Abrasion-Induced Erosion

For further investigations, it was hypothesized that the surface of soft sediment is eroded due to abrasion of hard and coarse material such as sand, gravel and shells. Experiments were conducted by letting a small amount of coarse sand flow over the surface of soil in the laboratory tray under flowing water to see whether abrasion induced erosion. Also, local scour is often noticed in nature around large size obstructions such as bridge piers or even small obstacles such as rock outcrops. It was necessary to examine whether local erosion of stiff cohesive soil is induced by small protrusions such as stones, gravel and shell. Hence these were embedded in the laboratory tray filled with field sediment and flow was generated. It was observed that with the maximum bed shear stress (3.0 Pa) generated in the sediment tunnel, neither of the two possible factors induced any erosion of the bed. These experiments were very preliminary in nature. They do not include effect of abrasion caused by large size sediment such as gravel. It is possible that local

erosion may occur at higher flows/different turbulence structure or at high concentration of suspended sediment in the eroding fluid.

Erosion Experiments on Core Samples

Out of the two core tubes received from the field, a 6-inch-long piece was cut from each and sent to the University of California, Davis for conducting the rotating-cylinder erosion experiments. These samples were used intact following procedures similar to those used for the surface sample. These experiments provided the following values:

Sediment	Critical Shear Stress for Erosion (Pa)	
	Sea Water	Deionized Water
KFB-31 U1 (44 - 46 feet)	> 8.0	4.2
KFB-31 U3 (74 - 76 feet)	4.2	2.3

Significant effect of erosion fluid composition was again demonstrated in these experiments. Sediment characterization of the two samples included determination of water content and sodium adsorption ratio. Sodium Adsorption Ratio (*SAR*) is defined as

$$SAR = \frac{Na^{+}}{\left[\frac{1}{2}\left(Ca^{++} + Mg^{++}\right)\right]^{\frac{1}{2}}} \tag{1}$$

where the concentrations of sodium (*Na*), calcium (*Ca*), and magnesium (*Mg*) ions are in milliequivalents per liter. The *SAR* is used as an index to characterize the pore fluid and eroding fluid in terms of the relative strengths of sodium, calcium, and magnesium ions. The results are given below :

Parameter	KFB-31 U1	KFB-31 U3
Water Content	44.2 %	44.3 %
Pore Fluid *SAR*	34	17
Eroding Fluid *SAR*	45	45

The rate of erosion curves for the above two core samples are presented in Figures 16 and 17 respectively. Both these figures give rate of erosion as a function of bed shear stress. The critical shear stress for erosion as well as the rates of erosion of sample U-3 are comparable to the corresponding values for surface sample # 8, indicating similarity in shear strength of soil with depth.

4 Conclusions

The cohesive as well as non-cohesive surface sediment in the area of Indian River Inlet may have a high potential of erosion under the existing flow-induced bed shear stresses. The values of sediment-related parameters given in this report will enable preliminary estimation of erosion rates once the flow-induced bed shear stresses are estimated.

The magnitude of critical shear stress for erosion and the erosion rates obtained in the laboratory experiments are consistent with the values reported in literature for similar values of sediment characterization parameters such as organic contents, silt and clay content and composition of eroding fluid.

The threshold shear stress for erosion was at least 4.2 Pa while at 10 Pa erosion rates ranged from about 0.004 - 0.025 g/cm^2/min.

In addition to surface erosion, severe erosion at the site may have also resulted from the following possible reasons:

a. Strong local eddies causing mass erosion

b. Unusual geological formation

c. Weakening of bed under varying salinity and /or high turbulence

d. Flow concentration caused by non-uniform flow velocity distribution

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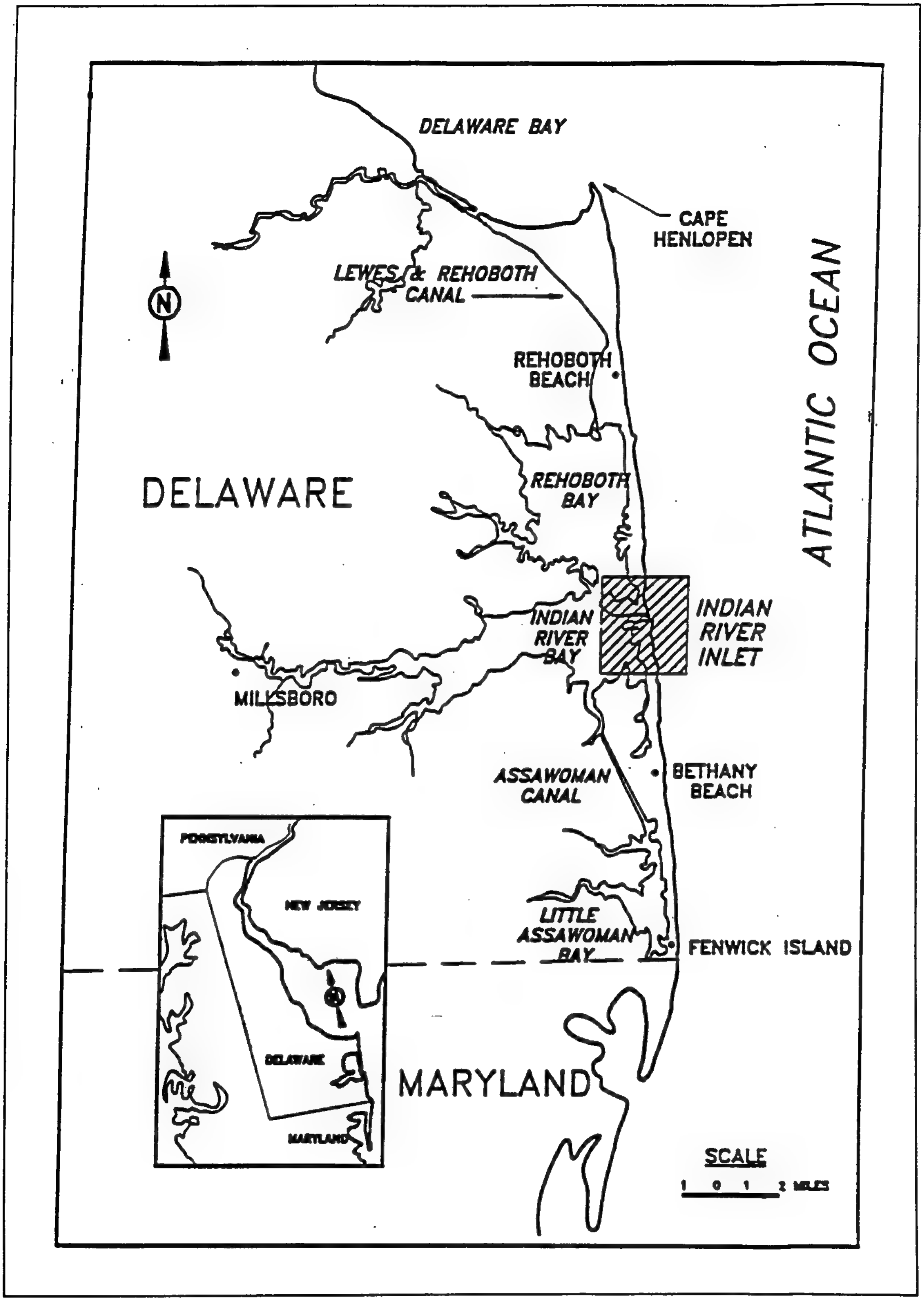

Figure 1. Location map of Indian River Inlet

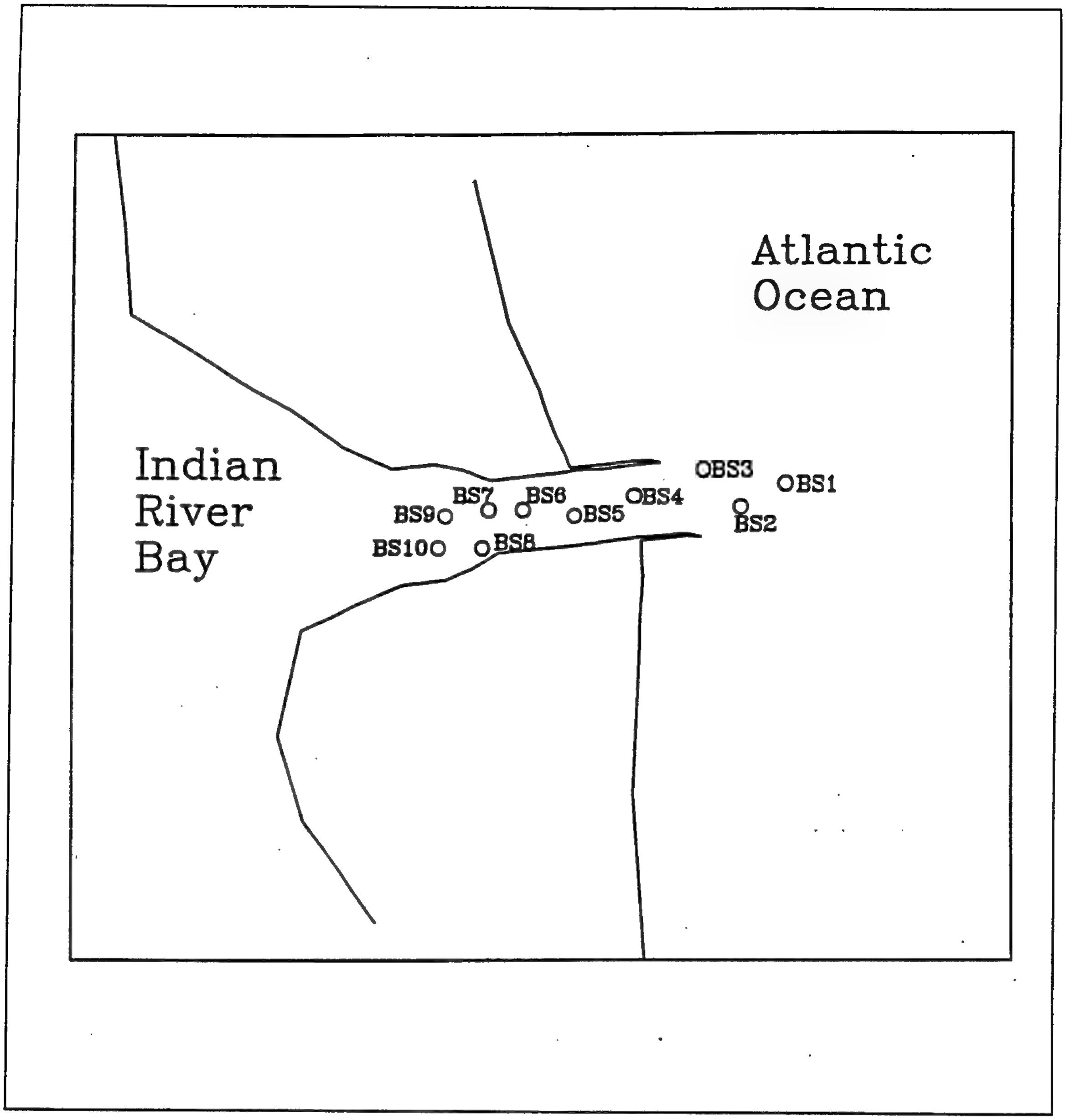

Figure 2. Locations of surface bed samples

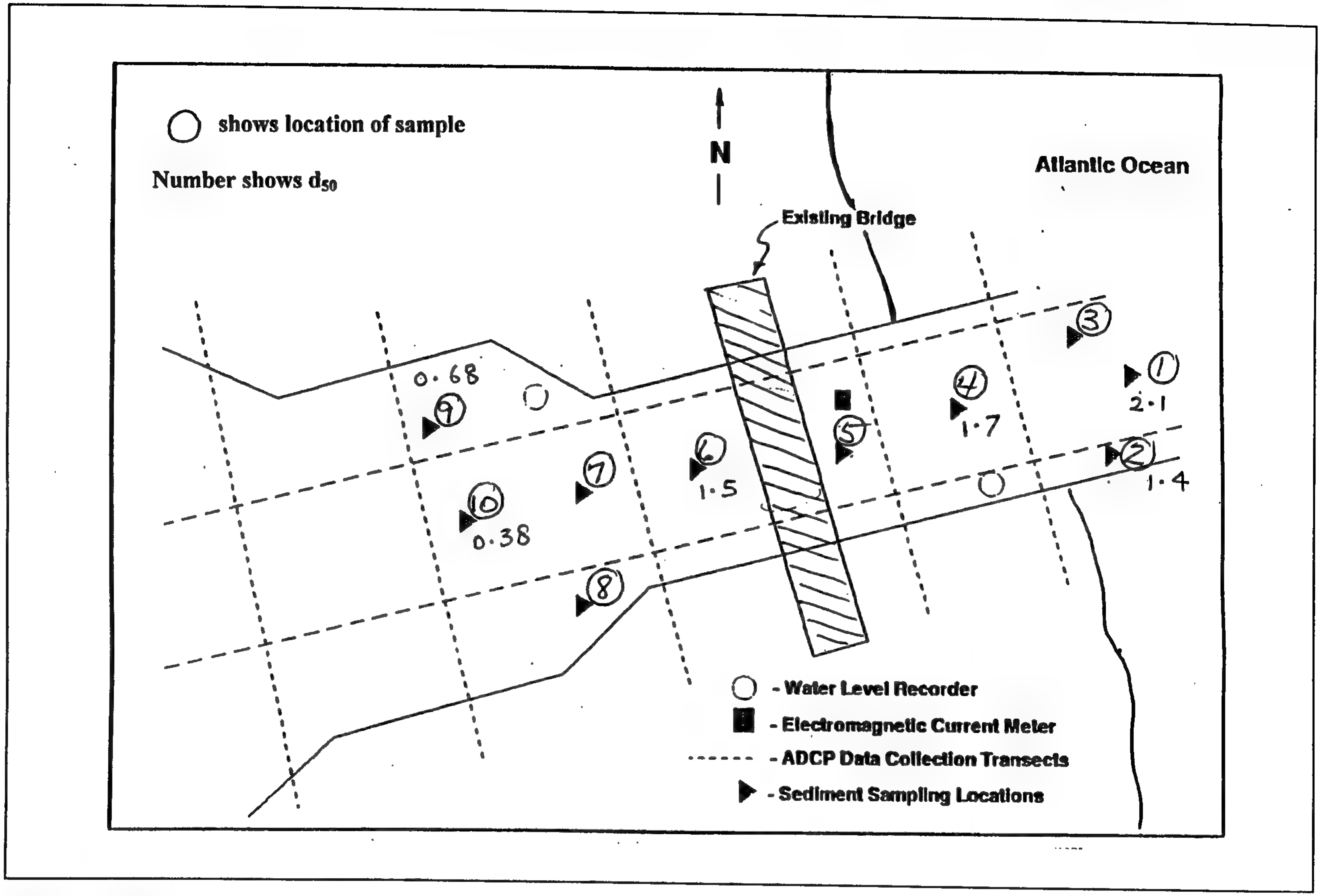

Figure 3. Median size (d_{50}) of surface bed samples

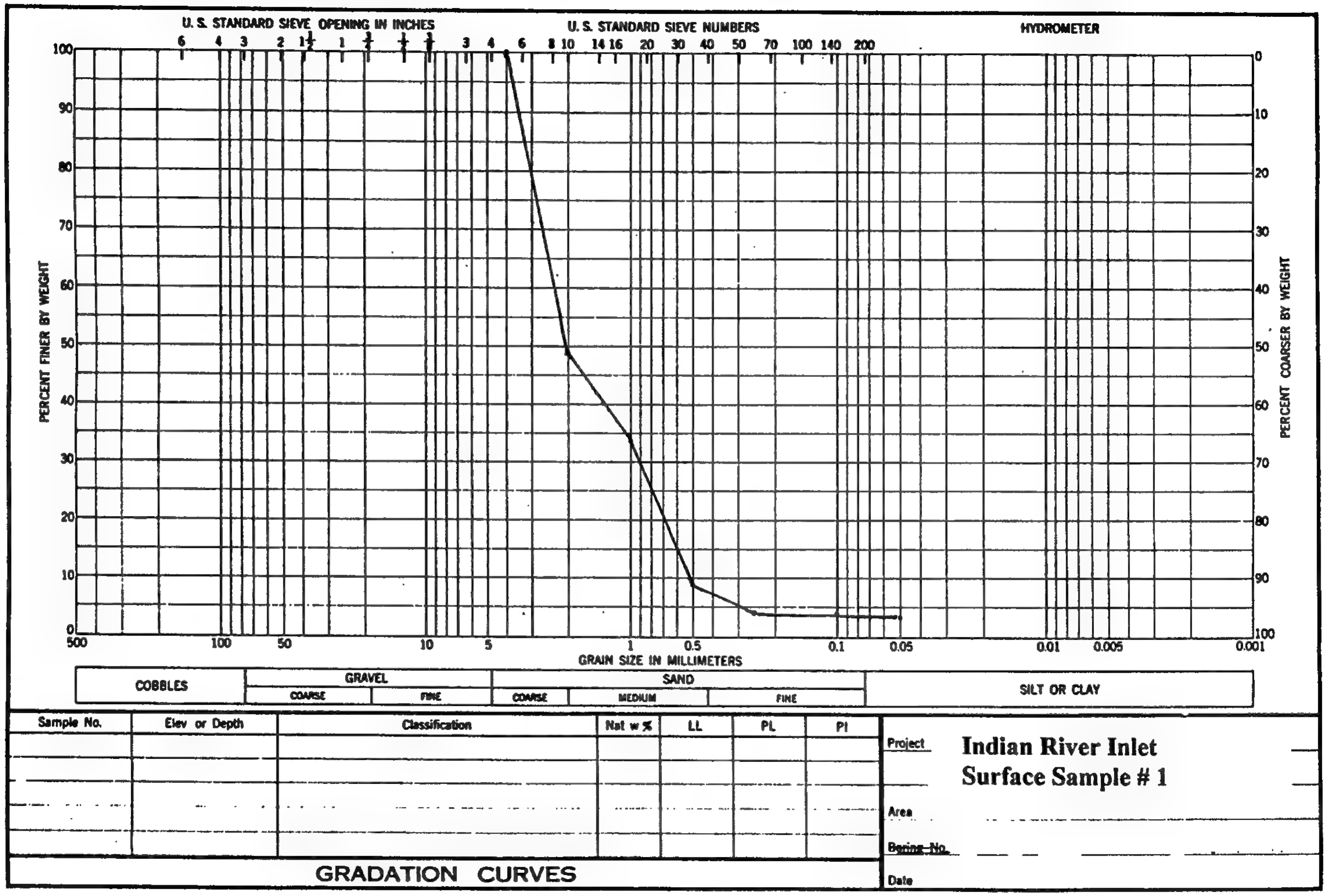

Figure 4. Size distribution of surface bed sample at location # 1

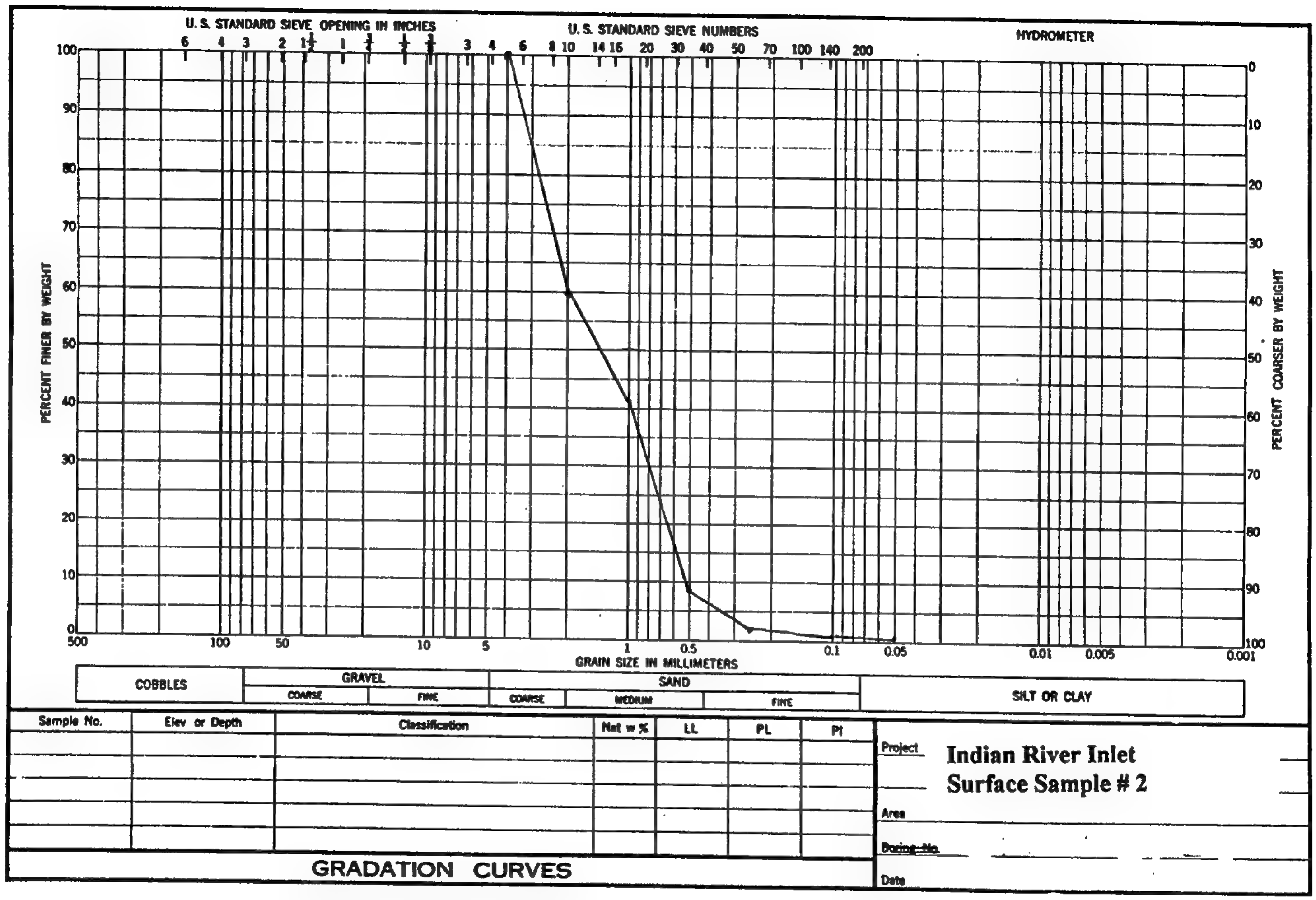

Figure 5. Size distribution of surface bed sample at location # 2

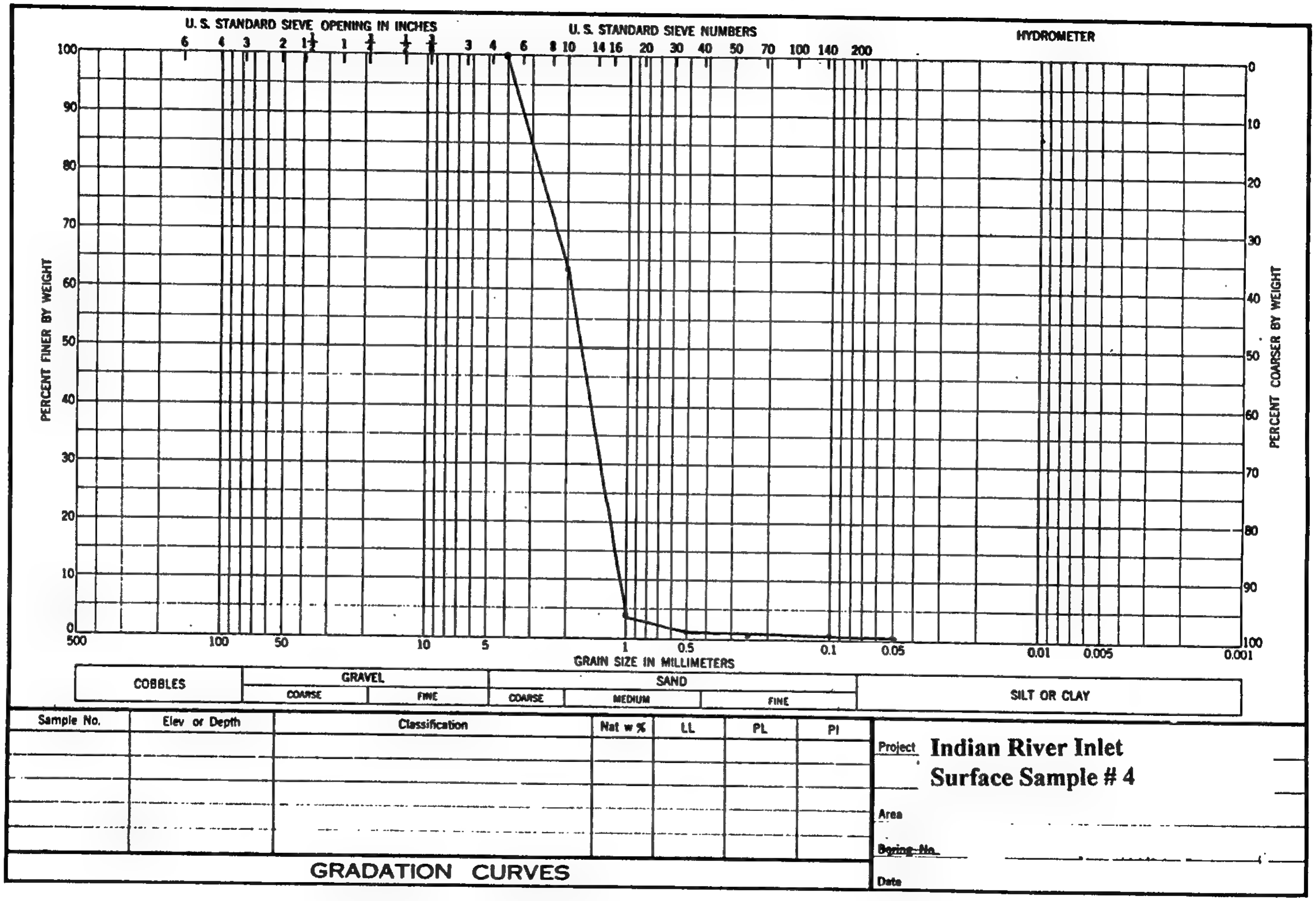

Figure 6. Size distribution of surface bed sample at location # 4

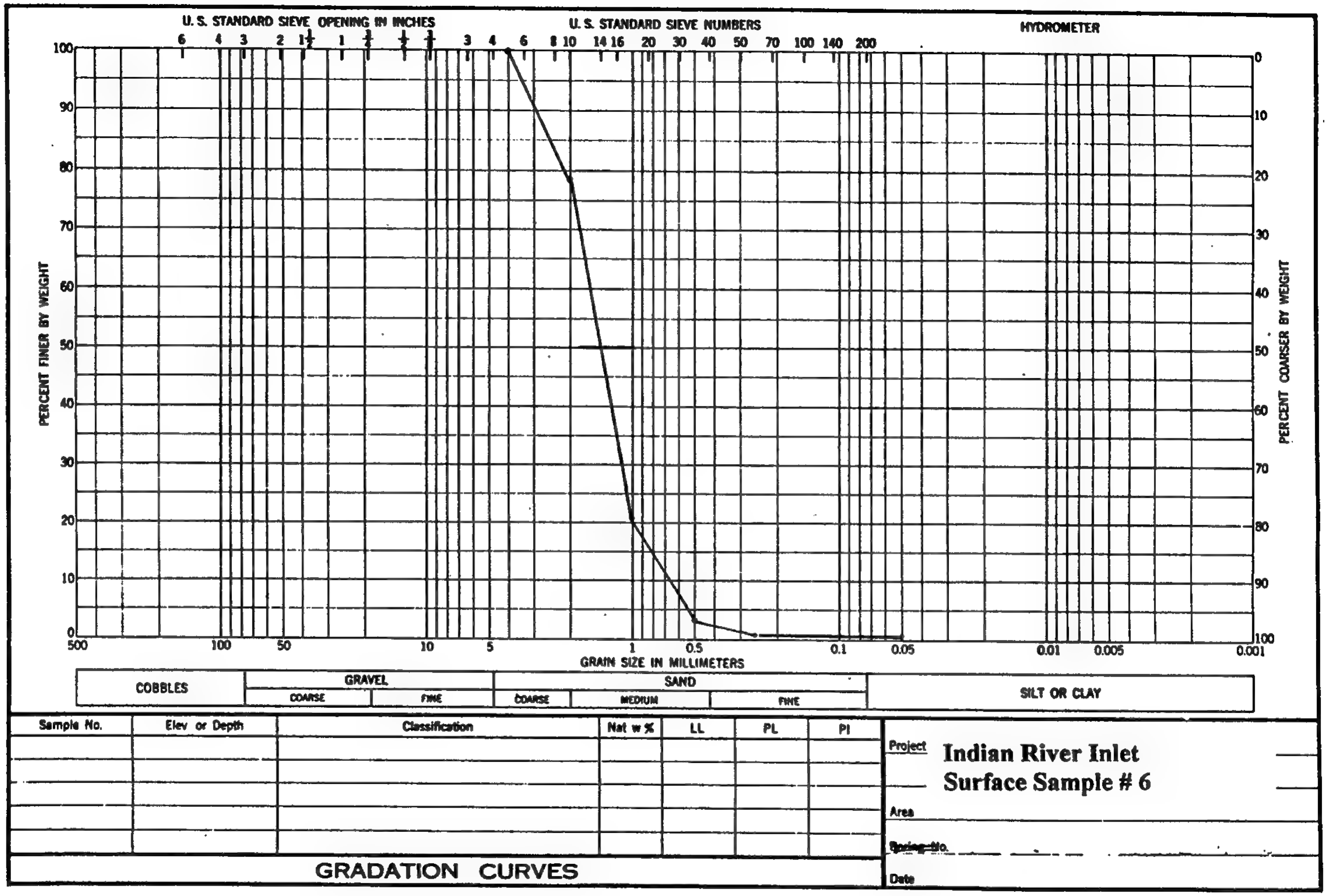

Figure 7. Size distribution of surface bed sample at location # 6

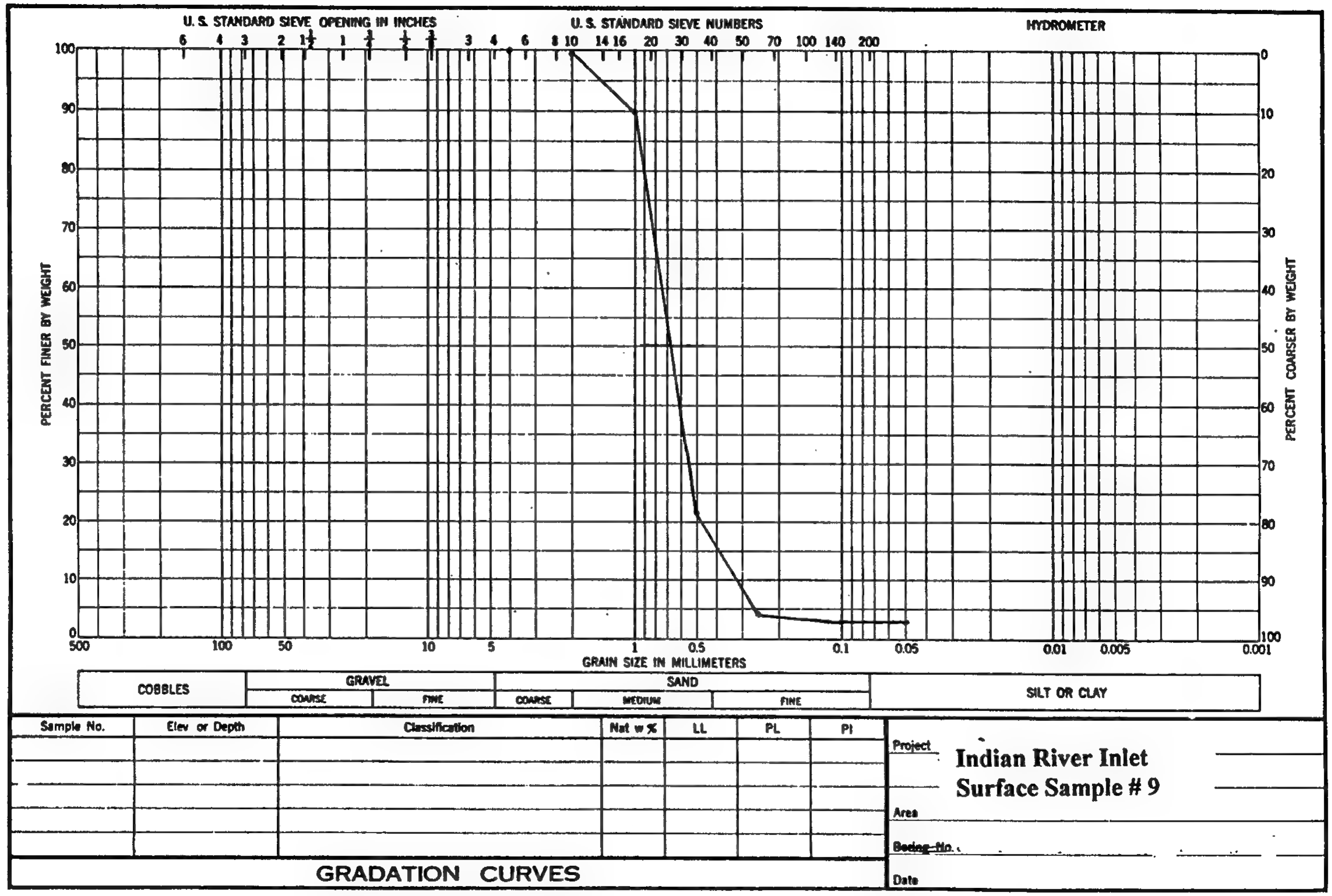

Figure 8. Size distribution of surface bed sample at location # 9

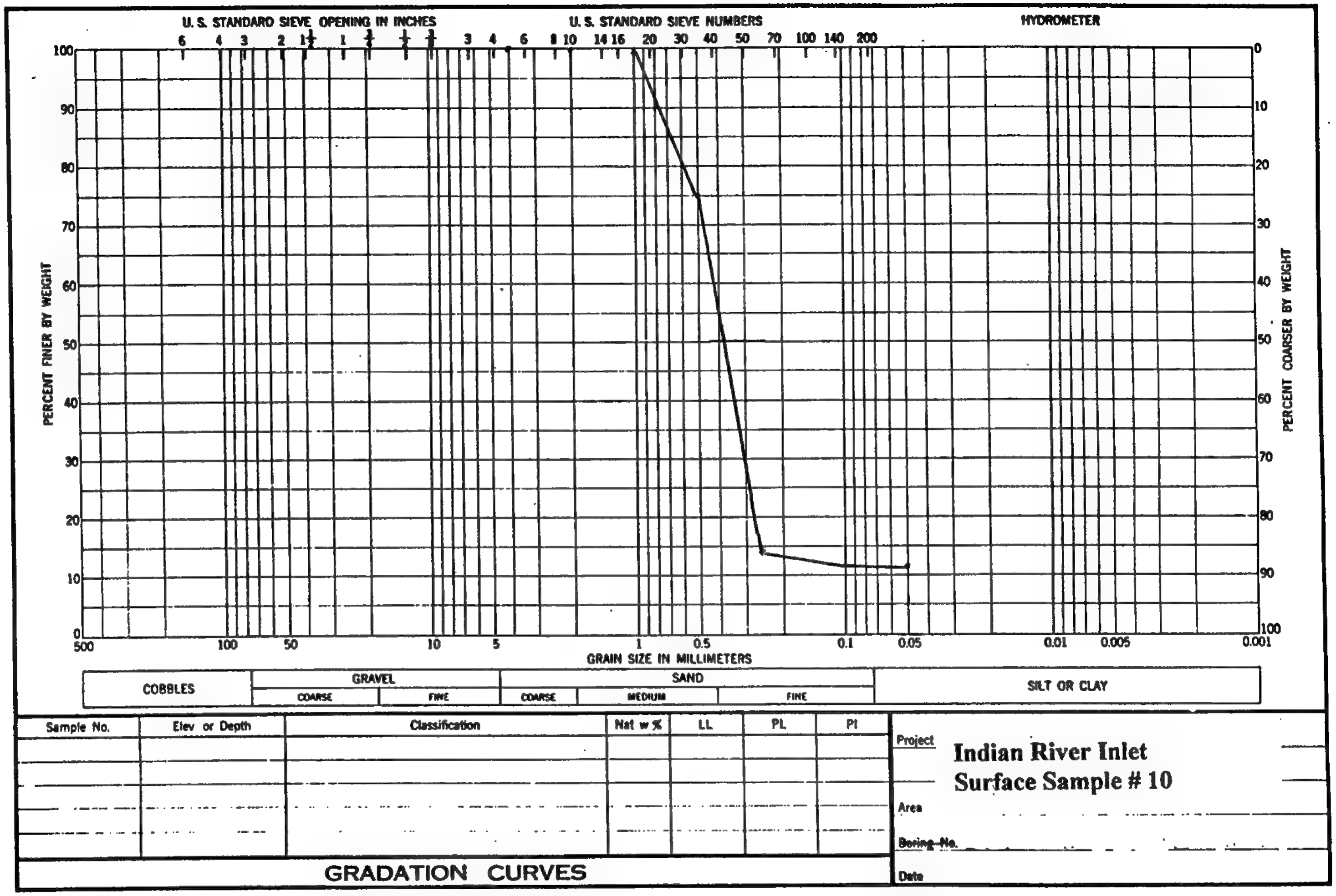

Figure 9. Size distribution of surface bed sample at location # 10

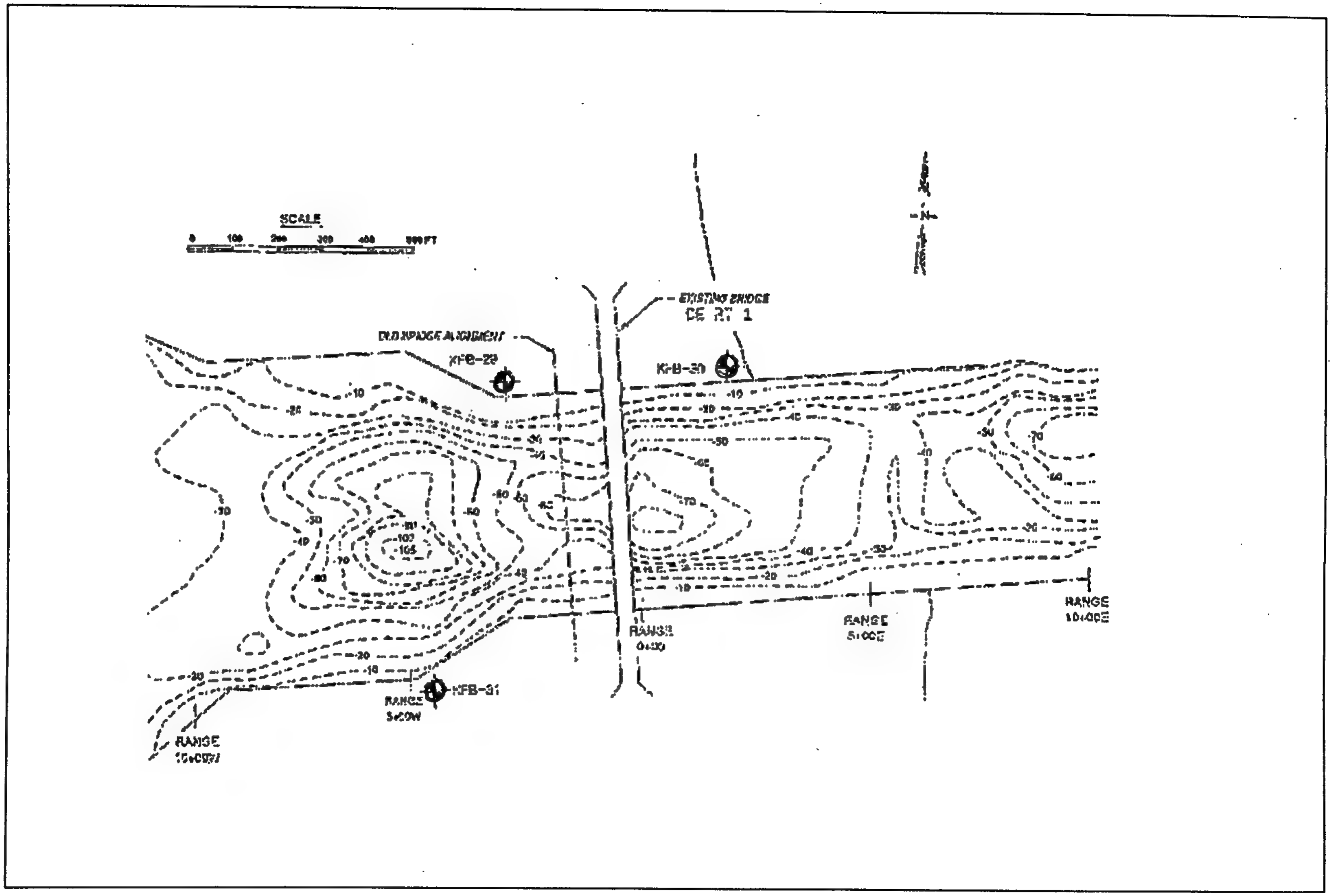

Figure 10. Locations of bore holes

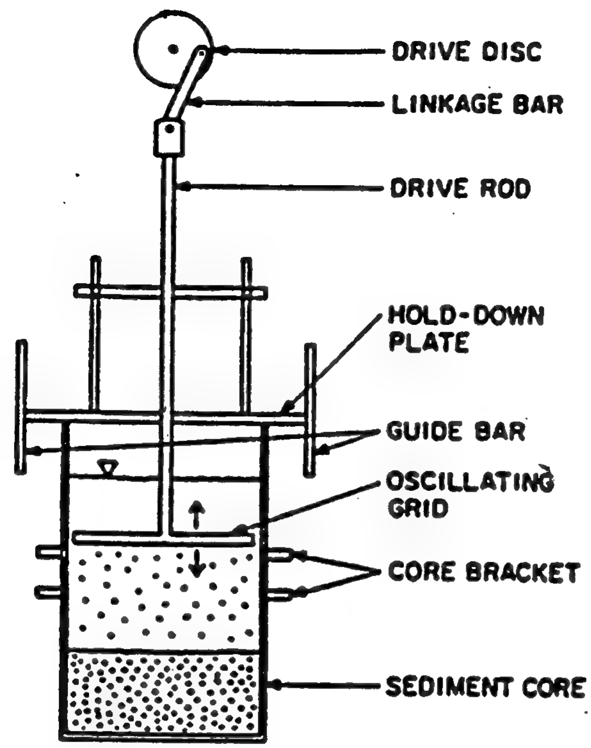

Figure 11. Particle Entrainment Simulator at WES

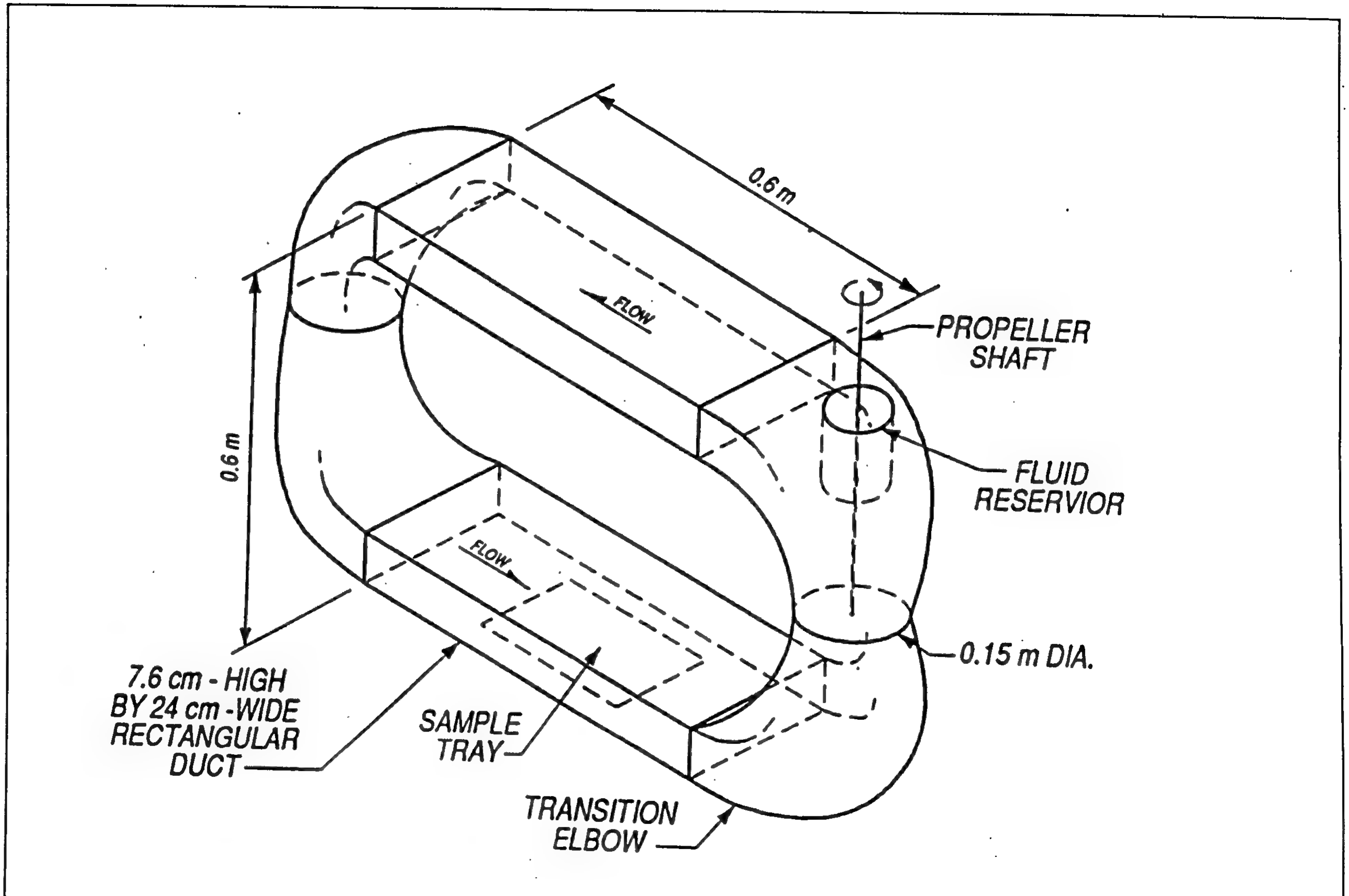

Figure 12. Vertical Loop Sediment Tunnel at WES

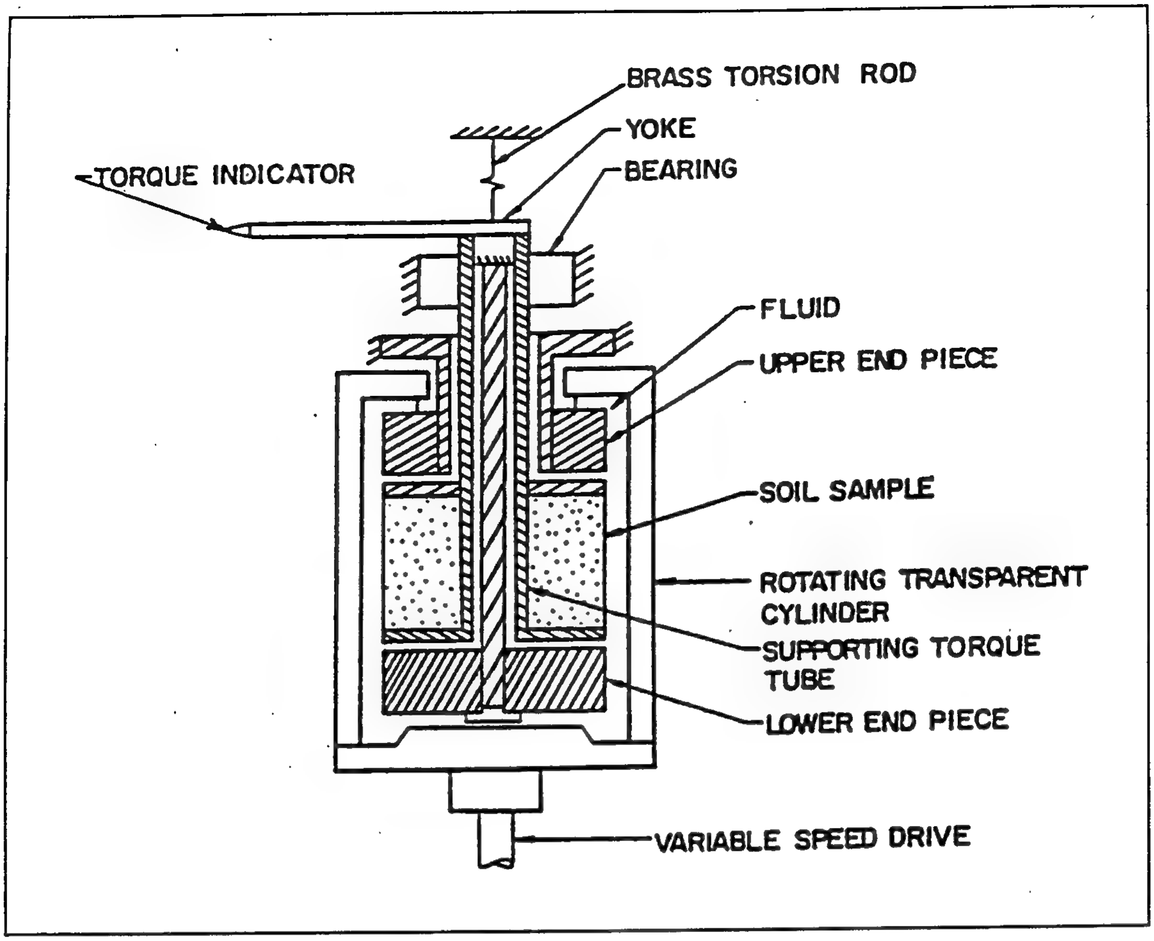

Figure 13. Rotating Cylinder Apparatus at University of California, Davis

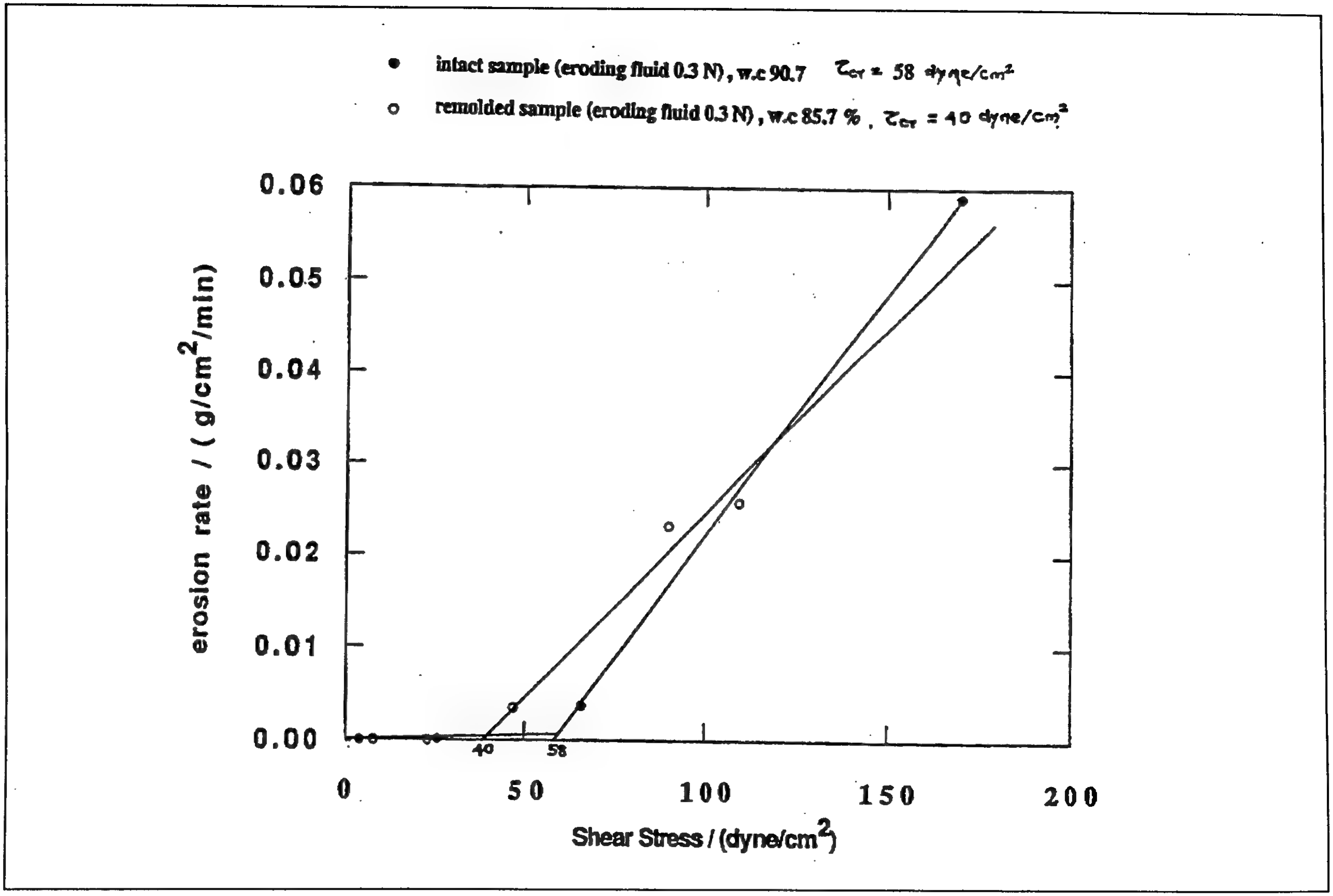

Figure 14. Results of erosion experiment on bed sample at location # 7

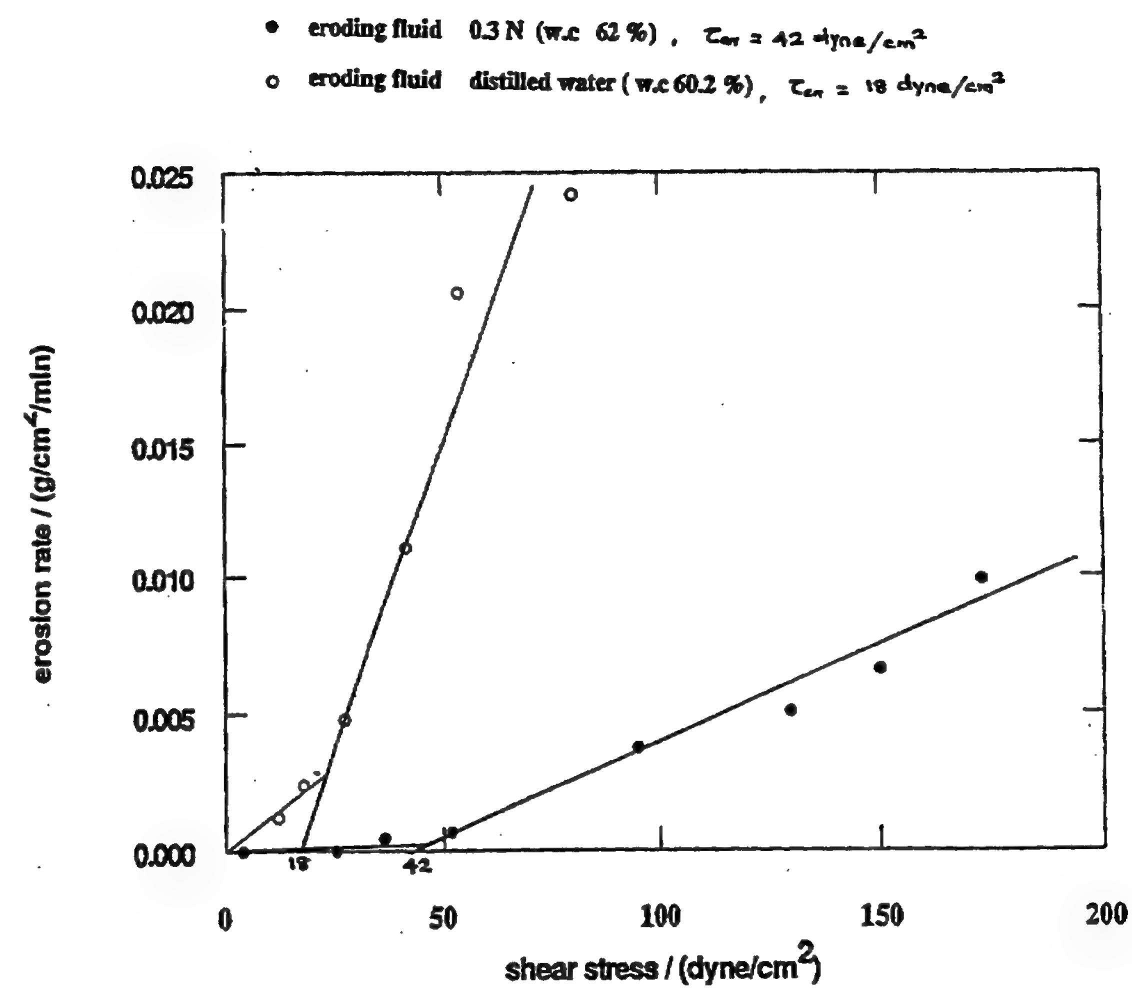

Figure 15. Results of erosion experiment on bed sample at location # 8

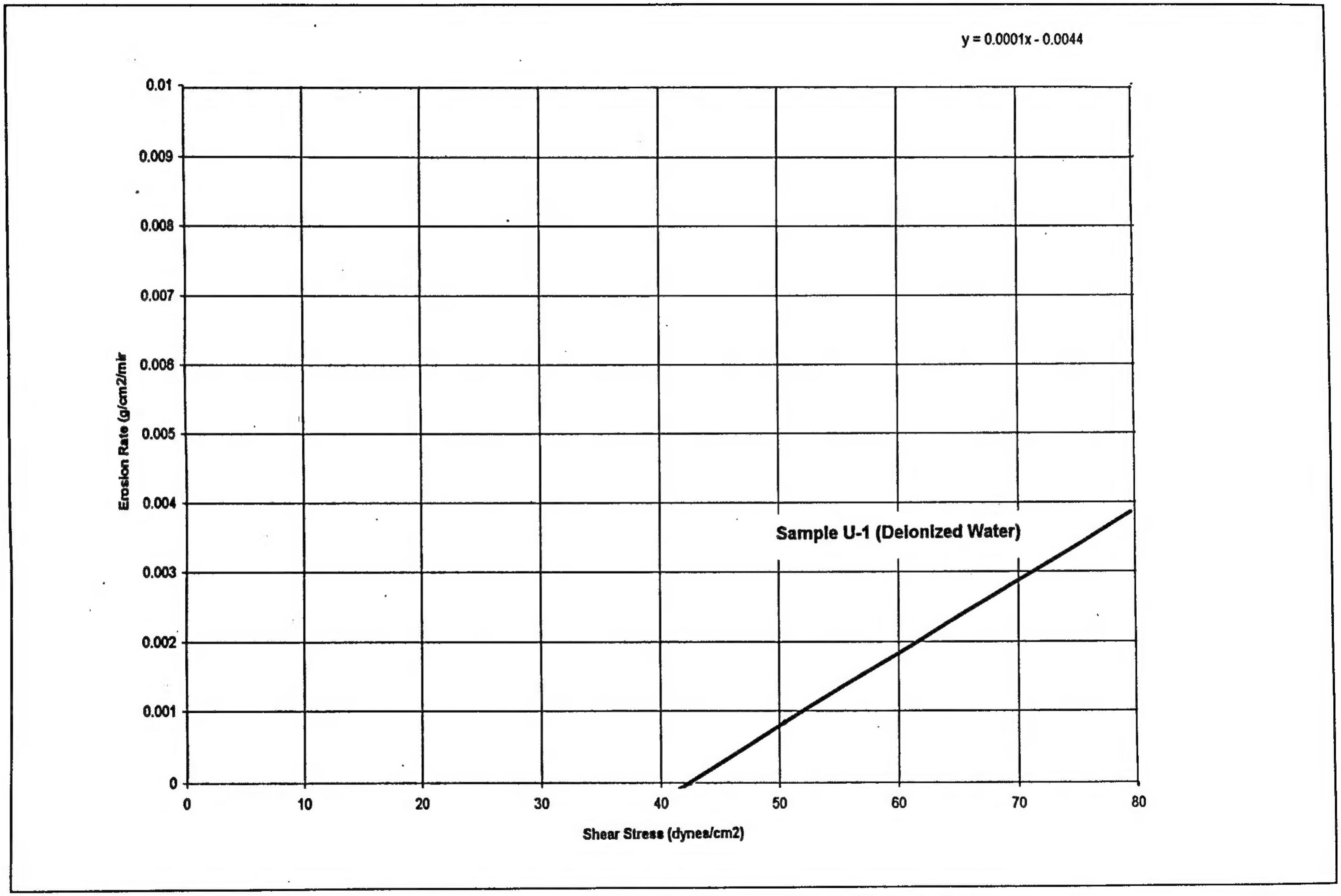

Figure 16. Results of erosion experiment on core sample U-1 at 44 - 46 feet depth

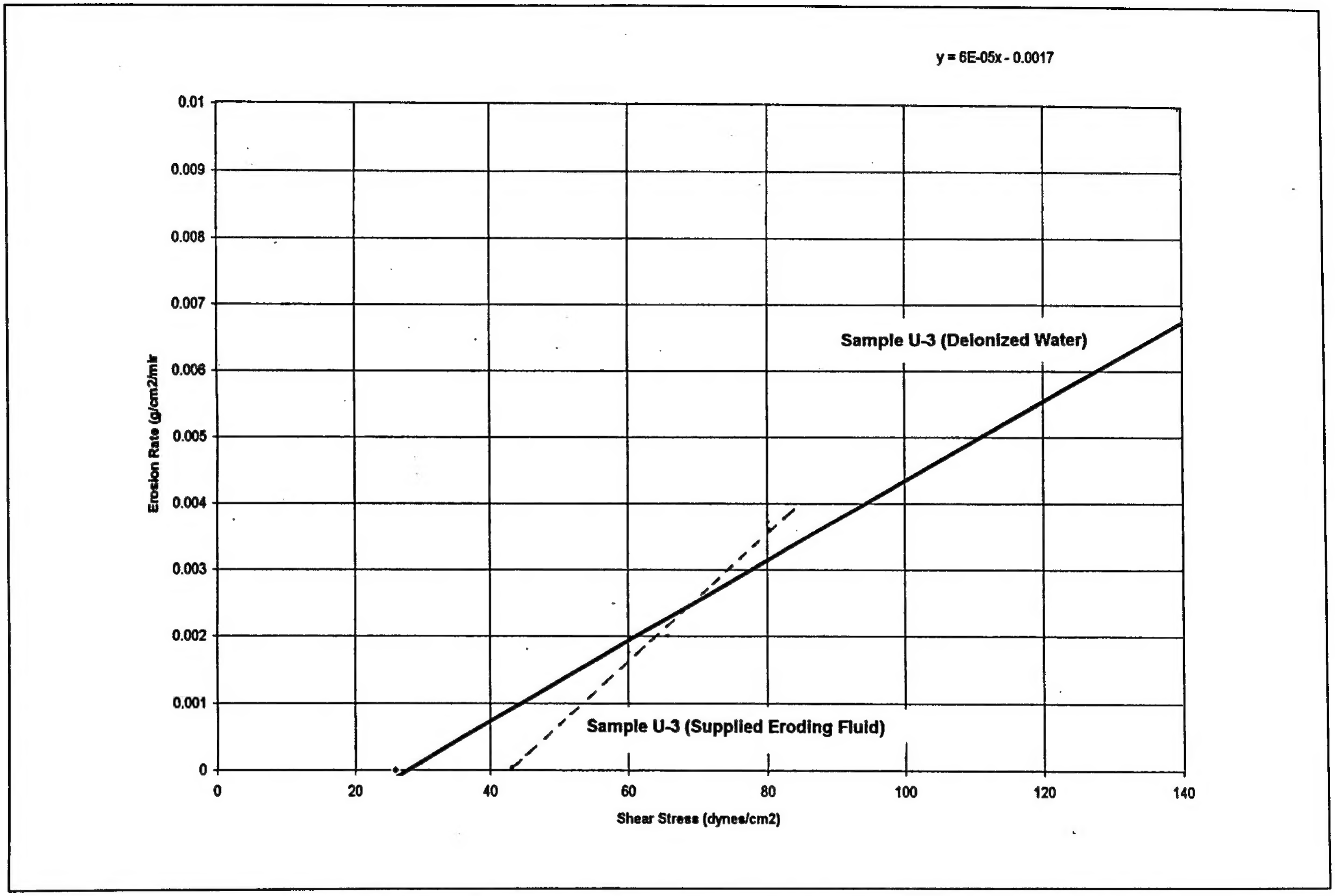

Figure 17. Results of erosion experiment on core sample U-3 at 74 - 76 feet depth

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13. ABSTRACT *(Maximum 200 words)*

Severe local erosion reaching depths up to 33.5 m (110 ft) has occured during the past few years near the mouth of Indian River Inlet in the State of Delaware. It is feared that the erosion may extend and endanger the bank riprap stability. The problem was investigated by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, at the request of the U.S. Army Engineer District, Philadelphia. Field data collected at the site in June 1994 included sediment samples and current measurements using ADCP. Laboratory tests were conducted on the sediment samples obtained from the site in order to determine the sediment chracterization, critical shear stress for erosion, and the rate of erosion under different bed shear stresses. Analysis of current data combined with the results of sediment experiments did not provide conclusive reasons for the severe erosion experienced at the site; however, the data will be useful for future investigations including modeling.

14. SUBJECT TERMS

Cohesive sediments	Indian River	Scour
Erosion	Inlet sediments	

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